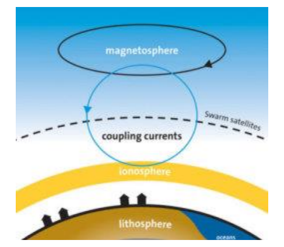
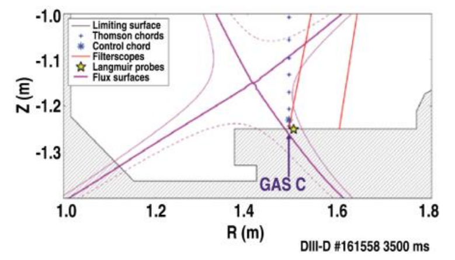
Introduction and Motivation

- Neutral/plasma boundary layers appear throughout nature, particularly in space and astrophysical plasmas. The physics at such boundaries is not well understood.



Magnetosphere/ionosphere transition in earth's atmosphere

Coronal/chromosphere transition in the sun



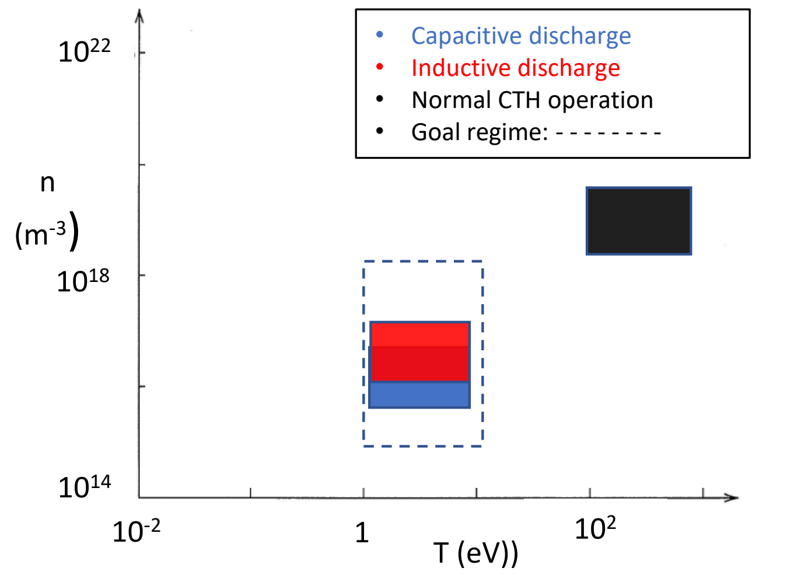
Detached divertor in fusion experiments

Substantial changes in the degree of ionization leads to new effects in:

Reconnection
Alfven wave dynamics
Cowling resistivity
Code validation in this regime

- We use a triple probe to investigate the plasmas generated through Electron Cyclotron Resonance Heating.

We use CTH to attempt to access a range of electron temperatures and fractional ionizations

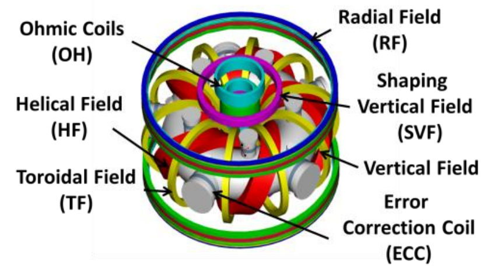


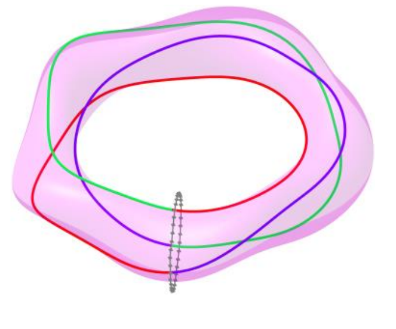
CTH can decouple plasma production and confinement through the use of stellarator fields and microwave heating

CTH low temperature plasma parameters:

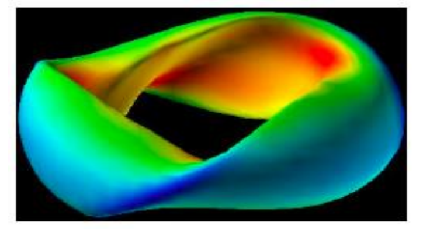
- $n_e = 5 \times 10^{14}\ m^{-3}$ to $5 \times 10^{18}\ m^{-3}$
- T_e = 1-15 eV
- ECRH Input Power ≤ 10 kW

CTH can create magnetic surfaces of constant temperature and density using a stellarator coil set





If a field line returns to its starting position, it creates one part of a magnetic surface.



A combination of toroidal, poloidal, and helical field coils twist field lines into a stellarator configuration.

$$D = (\Delta x)^2 \nu$$

$$\Delta x_\perp = r_L^e$$

$$\Delta x_\parallel = \lambda_{mfp}^e$$

- P = 1 mTorr
- $n_{neutral} = 3.55 * 10^{19}\ m^{-3}$
- $T_e = 10\ eV$
- $T_i = 1\ eV$

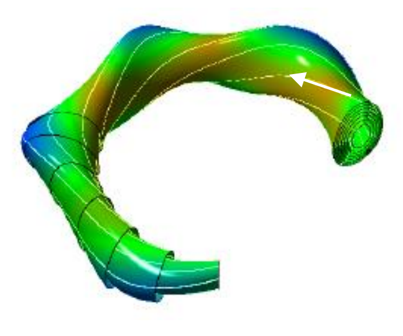
Random walk estimate = (step size)² x collision frequency

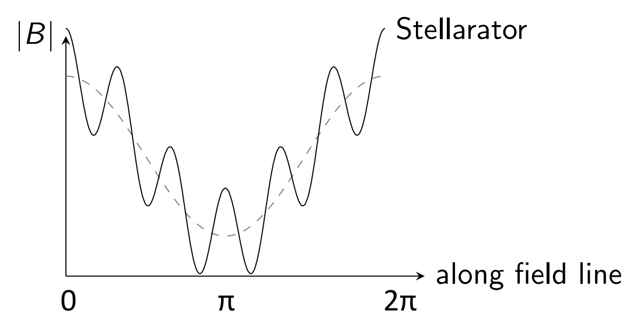
$$D_\perp^e = 1 * 10^{-3}\ cm^2/s \quad D_\parallel^e = 4 * 10^5\ cm^2/s$$

$$D_\perp^a = .88\ cm^2/s \quad D_\parallel^a = 477\ cm^2/s$$

$$D_\perp^i = .88\ cm^2/s \quad D_\parallel^i = 477\ cm^2/s$$

Particles collide with neutrals before encountering variations in magnetic field strength

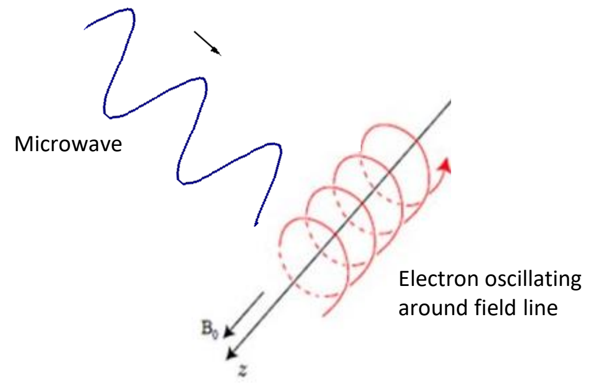




$\Delta x_\perp = r_L$ r_L^i = .16 cm, r_L^e = .0012 cm

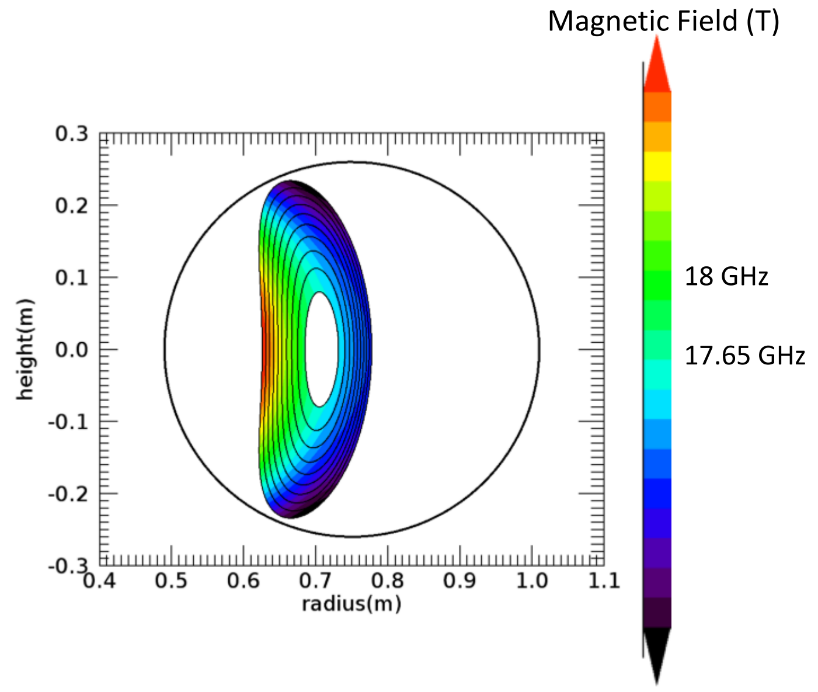
$\Delta x_\parallel = \lambda_{mfp}$ λ_{mfp}^i = 3 cm, λ_{mfp}^e = 30 cm

CTH can use Electron Cyclotron Resonance Heating to achieve a range of plasma parameters



Electrons oscillate around field lines at electron cyclotron resonant frequency:

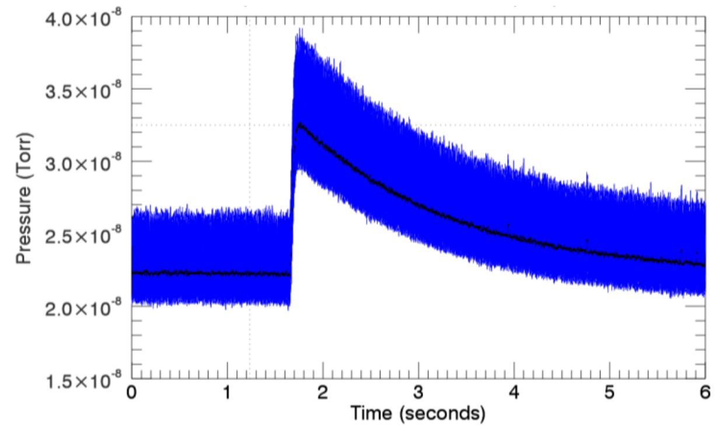
$$f_{ce} = \frac{eB}{2\pi m_e}$$



We energize electrons by inputting microwaves with a frequency of 17.65 GHz (0.630 T) and 18 GHz (0.643 T)

Neutral density estimated through change in pressure

Shot 17030803, 2.24 volts on gas valve



- We adjust input gas quantity through a voltage on a piezoelectric valve.
- With a known change in pressure, assuming room temperature, we have been able to estimate neutral density within chamber:

$$P = nk_BT$$

- This is an estimate which is inaccurate when hitting high fractional ionization levels.
- Going forward we hope to use spectroscopy to more confidently determine neutral density through the H-α line

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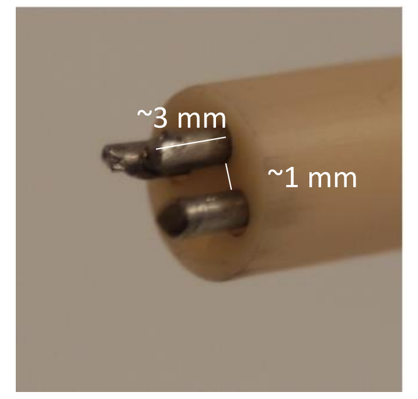
- U.S. Department of Energy Grant No. DE-FG02-00ER54610

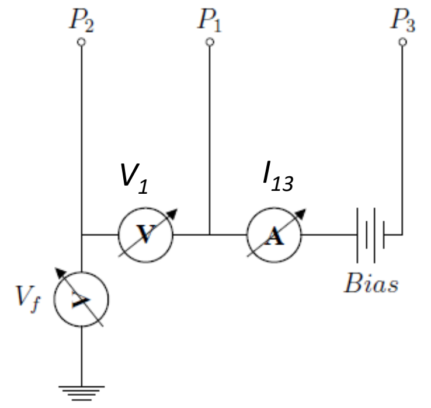
Triple probe allows for local measurement of plasma parameters



Given:

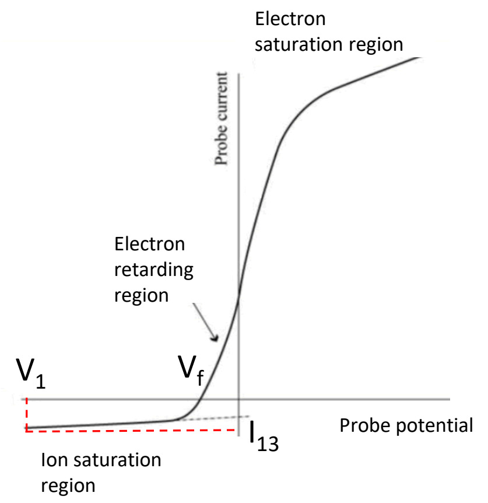
- T_e = 10 eV
- $n_e = 4.5 \times 10^{11}\ cm^{-3}$

Debye Length:
0.035 mm << 1 mm probe tip spacing

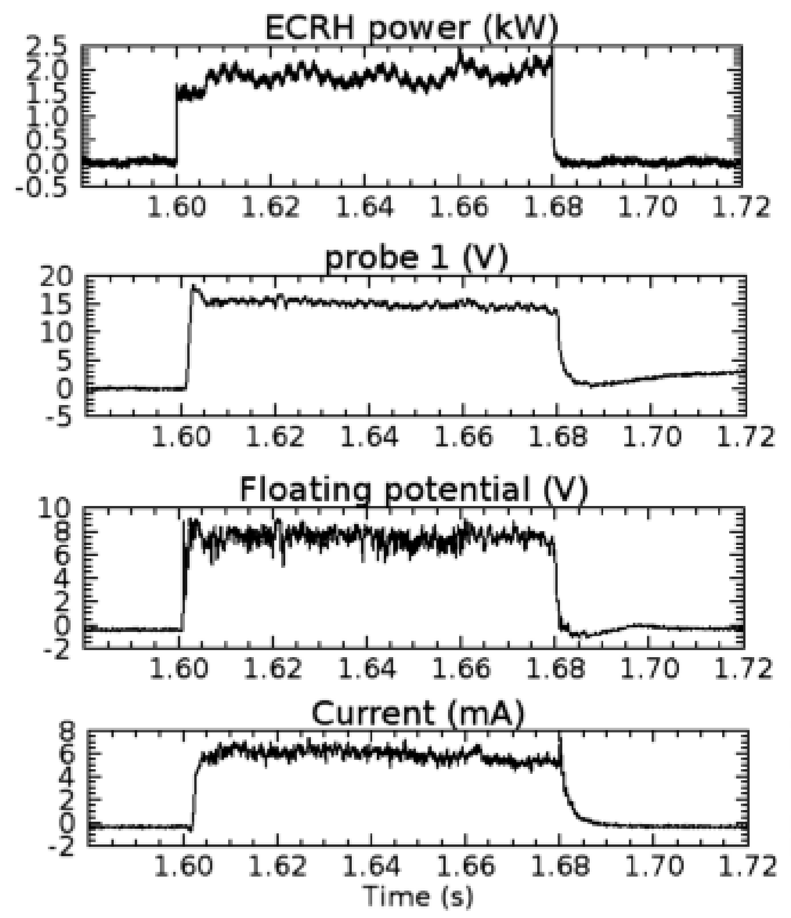


$$T_e = \frac{V_1 - V_f}{\ln(2)} \qquad n_e = \frac{I_{13}}{eA}\sqrt{\frac{m_i}{k_B T_e}}\, e^{0.5}$$

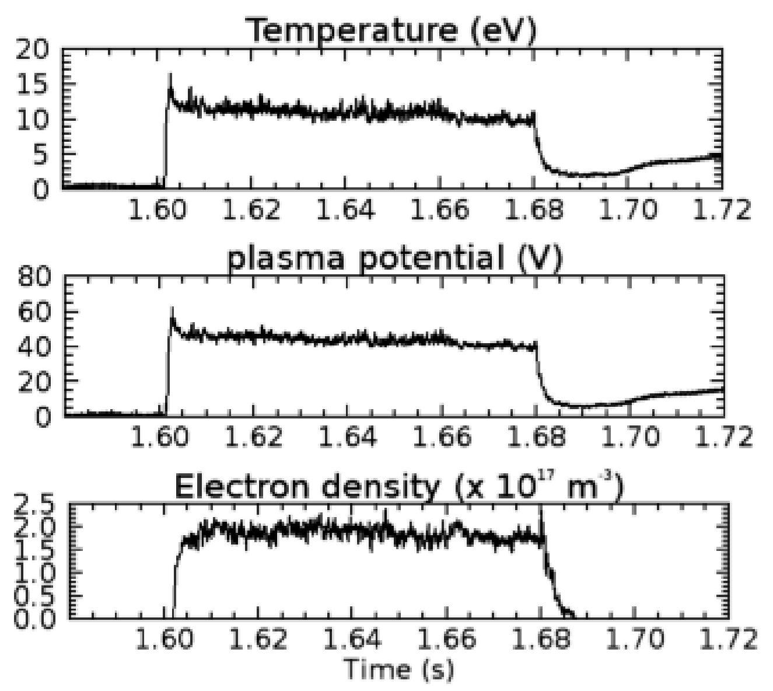
$$V_p = \frac{k_b T_e}{2e}\left[\ln\left(\frac{m_i}{2\pi m_e}\right) + 1\right] + V_f$$



Raw Data

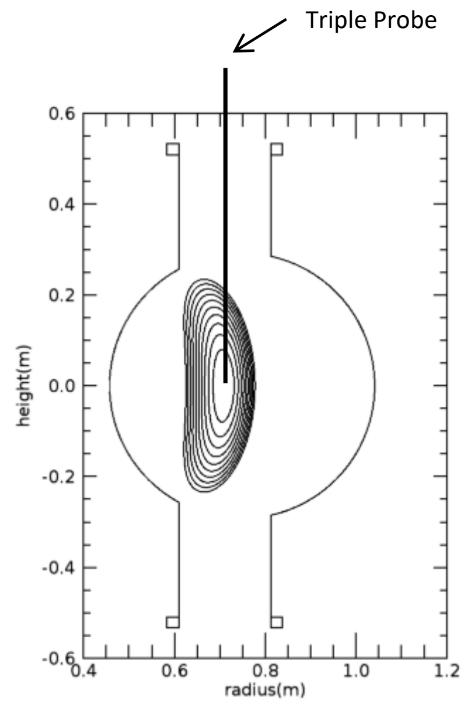


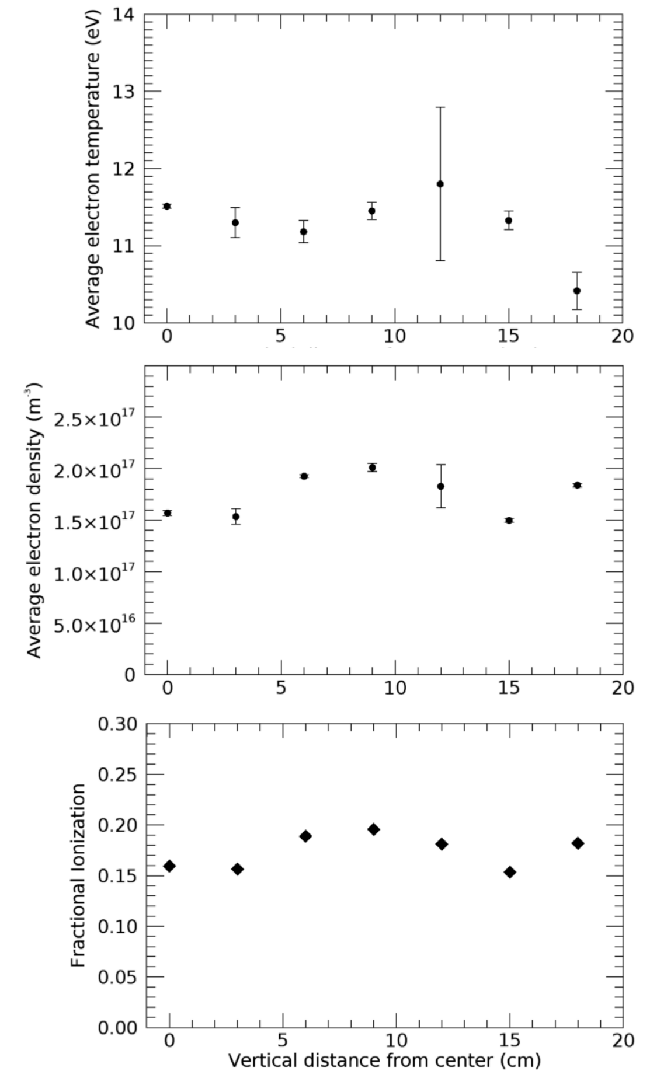
Processed Data



Profile of Electron Density and Temperature

- Profile measured by changing probe position between shots
- ECRH power ranges from 1.77 kW to 1.87 kW (5% change)
- Input neutral density fixed at $8.3 \times 10^{17}\ m^{-3}$





Uniform discharge model for particle and energy balance

Assume:

- Steady state
- Cylinder of length $\pi {R_0}^2$, radius a
- Plasma created through ionization
- Both n_g and n_p uniform throughout

Particles lost due to diffusion = plasma generated by ionization

$$\cancel{n}_e \vec{v} A = \cancel{n}_e n_g \pi a^2 \pi {R_0}^2 K_{iz}(T_e)$$

$$\vec{v} A = K_{iz}(T_e) n_n \pi^2 a^2 R_0$$

Assume: $\vec{v} = D_\perp^a \frac{\nabla n}{n} = D_\perp^a \frac{1}{a}$

$$D_\perp^a \frac{A}{a} = K_{iz}(T_e) n_n \pi^2 a^2 R_0$$

$$\boxed{\frac{2D_\perp^a}{a^2 n_n} = K_{iz}(T_e)}$$

Temperature depends explicitly on neutral density, but electron density does not.

Power absorbed by the plasma = power leaving the plasma through diffusion

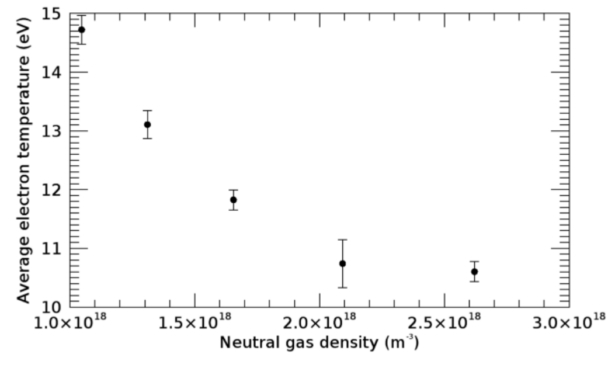
$$P = n_e \vec{v} A \varepsilon_T e$$

$$P = n_e \frac{D_\perp^a}{a} A \varepsilon_T e$$

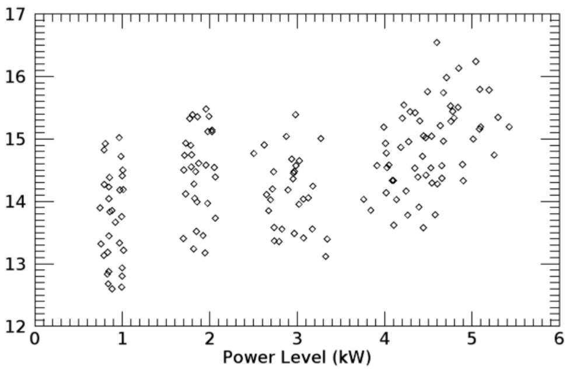
$$\boxed{n_e = \frac{P}{D_\perp^a \pi a \varepsilon_T e}}$$

Electron density depends explicitly on input power but temperature does not.

Electron temperature in hydrogen is more affected by neutral gas than power level, as suggested by particle balance

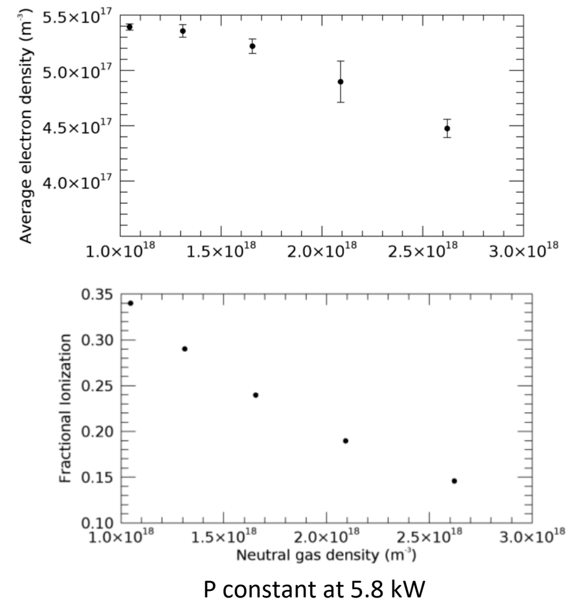


P constant at 5.8 kW

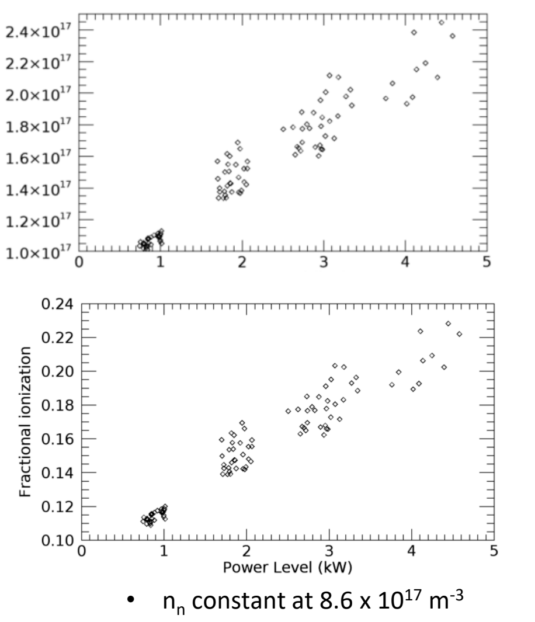


- n_n constant at $8.6 \times 10^{17}\ m^{-3}$
- Window size used: 4 ms

Neutral gas input quantity affects electron density by more than expected

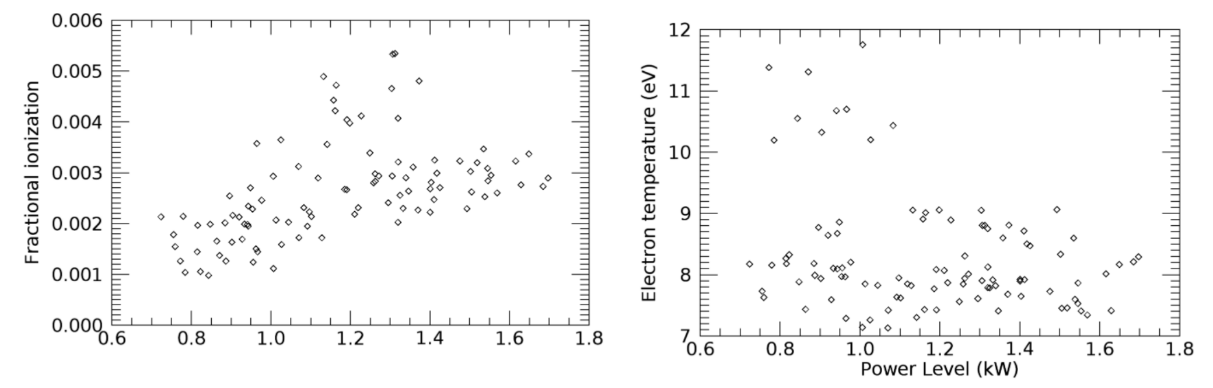


P constant at 5.8 kW



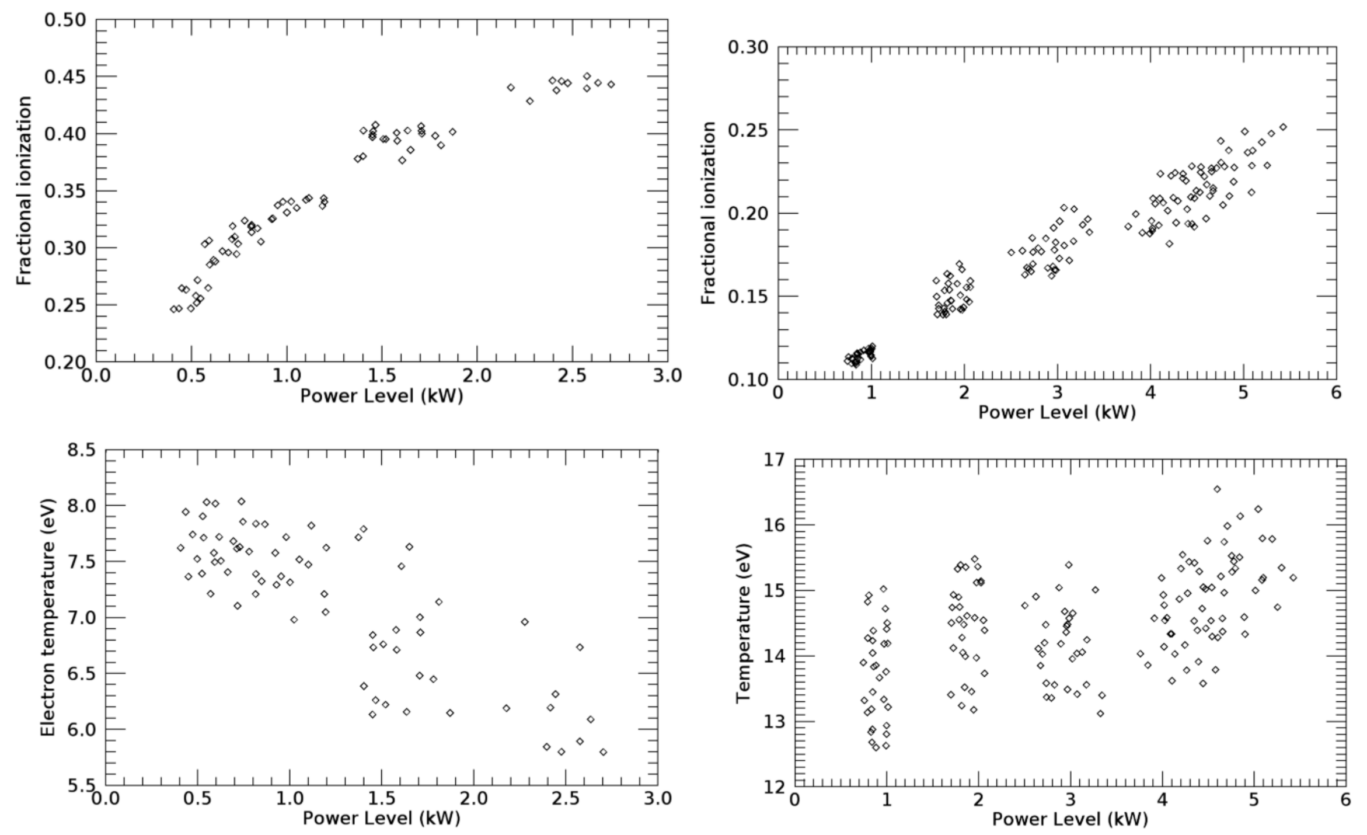
- n_n constant at $8.6 \times 10^{17}\ m^{-3}$
- Window size used: 4 ms

Lower fractional ionization levels appear achievable with hydrogen



- $n_n = 8.28 \times 10^{18}\ m^{-3}$, higher than $2.65 \times 10^{18}\ m^{-3}$ shown previously
- The range of 0.7 to 1.7 kW is lower than the range of 0.7-4.7 kW shown previously
- While other fractional ionizations appear high, accessing lower fractional ionizations appears possible

Like Hydrogen, power level in Argon plasma affects electron density more than electron temperature



Argon:

- $n_n = 1.31 \times 10^{18}\ m^{-3}$
- Have reached 6-8 eV
- Have reached fractional ionization of 25%-45%
- Temperature decreases with increasing power

Hydrogen

- $n_n = 8.6 \times 10^{17}\ m^{-3}$
- Have reached 10-15 eV
- Have reached fractional ionization of 10%-30%

Conclusions

- Using CTH to access a range of fractional ionizations
- Temperature and density both have fairly flat profiles
- As predicted by particle balance, temperature is more dictated by neutral density than power
- Electron density is dictated by neutral density more than is predicted by power balance
- We can reach fractional ionizations between 0.1 and 0.35 and temperature between 10 and 15 eV
- With aggressive gas puffing it appears we can achieve a fractional ionization of 0.001 and an electron temperature of 8 eV

References

[1] Lieberman, M. (2005). *Principles of Plasma Discharges and Materials Processing*. 2nd ed. New Jersey: John Wiley & Sons, Inc.

[2] Cianciosa, M. (2011). Measurements and Modification of Sheared Flows and Stability on the Compact Toroidal Hybrid Stellerator. *Auburn University*.